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# Physical-Parameter Identification of Torsionally Coupled Base-isolated Buildings

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***Abstract*— In this paper, a physical identification procedure considering the torsionally coupled effect is developed to investigate the dynamic characteristics of an asymmetric base-isolation building equipped with lead–rubber bearings. A rigid superstructure is assumed to approximate the dynamic characteristics of a squat base-isolated structure. The torsional stiffness of the isolation system is considered linear, whereas the translational stiffness in both the $x$ and $y$ directions is assumed bilinear. The hysteresis of the base shear in relation to the bearing displacement is characterized by a backbone curve, by which the multivalued force–deformation relationship can be transformed into a single-valued function, thus simplifying the system identification task. The proposed algorithm extracts the physical parameters of the isolation system in the three independent directions, thereby providing critical information for structural health monitoring. A numerical example is used to demonstrate the feasibility of the proposed technique for asymmetric base-isolated buildings**.

***Keywords*—Base-isolated building, Torsionally coupled model, Physical parameter identification, Lead–rubber bearings, Bilinear hysteretic model, Structural health monitoring.**

## I. INTRODUCTION

Seismic base isolation is an effective means of damage-proofing building structures against strong earthquakes. The purpose of base isolation is to lengthen the fundamental period of structures to avoid resonance with the predominant frequency contents of earthquakes. As a result, the seismic responses of a building can be reduced significantly more by using base-isolated than by using its non-isolated alternative. Various base isolation systems have been extensively studied both analytically and experimentally since the early 1970s and have been adopted worldwide. Among others, lead–rubber bearings (LRBs) are the most popular seismic isolation systems in New Zealand, Japan, the United States, Italy, China, Taiwan, and elsewhere.

System identification methods are adopted to estimate structural parameters, including isolation system, according to the recorded responses of the structures with or without input disturbance information. Although various dynamic testing methods have been developed for system identification purposes, it is not practical to identify the system parameters of a massive civil engineering structure through artificial loading tests of any form. However, seismic structural responses recorded during earthquakes provide insight at a modest cost into the structural behavior and dynamic characteristics of targets. Nagarajaiah and Sun [1] investigated the seismic performance of a base-isolated hospital building on the campus of the University of Southern California (USC). Using a bilinear model to represent the base isolation system, their study indicated that the identified responses exhibited favorable agreement with the observed data. The seismic isolation performance of the Fire Command and Control (FCC) building in Los Angeles was further explored by Nagarajaiah and Sun [2]. To characterize the dynamic properties of structural systems under impact loading, a two-dimensional analytical model with an impact spring-dashpot was proposed. Moreover, a three-degree-of-freedom analytical model accounting for the effects of eccentric impact loading was also developed to estimate the parameters of a torsion-coupling (TC) base-isolated building. The parameters identified from the seismic responses were closely related to the analytical model. Accordingly, the seismic performance of the base-isolated FCC building during the Northridge earthquake was proved to be satisfactory. Nagarajaiah and Dharap [3] also developed a new approach for the system identification of base-isolated buildings. A least-squares technique with time segments was proposed for the identification of piecewise linear systems. A series of equivalent linear system parameters was identified from segment to segment. A reduced-order observer was employed in the absence of full-state measurements to estimate the unmeasured states and initial conditions at each time segment. The evolving equivalent linear dynamic properties of the USC hospital building during the Northridge earthquake were determined using the proposed technique. The changes in system parameters, such as the frequencies and damping ratios, caused by the inelastic behavior of the LRBs were reliably estimated. Nagarajaiah and Li [4] conducted a system identification of the FCC building by using the same technique. Huang *et al.* [5] introduced a bilinear backbone curve to represent the pre-yielding and post-yielding stiffness of the isolators, thus converting the complex nonlinear problem into a piecewise linear one. Wang *et al.* [6] assessed the damage of the seismic isolators of the TC structures with various damage indices. The results showed that the proposed indices are capable of localizing damaged isolators.

A physical identification procedure considering the torsionally coupled effect is developed in this paper to investigate the dynamic characteristics of asymmetric base-isolation buildings equipped with LRBs. A rigid superstructure is assumed in this paper to approximate the dynamic characteristics of a squat base-isolated structure.

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The torsional stiffness of the isolation system is considered linear, whereas the translational stiffness in both the $x$ and $y$ directions is assumed bilinear. Because the stiffness of the isolation devices in both translational directions is nonlinear, direct identification of the parameters from the hysteresis is complicated. Therefore, a physical parameter identification procedure utilizing the backbone curve introduced by Huang *et al.* [5] is developed herein. In this manner, the multivalued restoring force can be transformed into a single-valued function, thus simplifying the identification analysis. A numerical example is provided to demonstrate the feasibility of the proposed technique for the physical parameter identification of asymmetric base-isolated buildings subjected to earthquake excitation.

## II. Motion Equation

Oliveto *et al.* [7] showed that the dynamic structural responses of an asymmetric base-isolation building are primarily contributed by the first three modes corresponding to those with a rigid superstructure when the isolator experiences large deformation. They have justified such a rigid superstructure assumption by collecting the acceleration records from each floor of the Solarino (isolated) building in Italy and comparing the Fourier spectra and phase angles of all the records. Their results show that the differences are very little from each other in the frequency range of the isolation mode. The maximum deviation from the mean of the resonance peaks is smaller than 4%, which indicates the motion of superstructure of the isolated building is similar as a rigid body. Jain and Thakkar [8] also stated that this assumption is feasible for non-isolated buildings with a fundamental period under 1.0 second (low-rise building), considering that the typical period of isolated structures is generally 2.0 seconds. Therefore, a model of a rigid superstructure on top of the base-isolation bearings (i.e., LRBs) is considered in this paper, as shown in Fig. 1. According to Oliveto *et al.* [7], if the Fourier amplitudes of measured responses of the isolated building between different floors are very close (less than 4% deviation from the mean of resonance peaks) with each other in the isolated mode, the proposed method can be applied.

The free body diagram of the rigid superstructure under large deformation in the isolation level is illustrated in Fig. 2, in which $m_p$ and $J_p$ represent the mass and polar moment of inertia of the building, respectively; $k_{iex}$ and $k_{iey}$ denote the pre-yielding stiffness coefficients of the $i$th isolator in the $x$ and $y$ directions, respectively; $c_{ix}$, and $c_{iy}$ refer to the damping coefficients of the $i$th isolator in the $x$ and $y$ directions, respectively; and $k_{i\theta}$ and $c_{i\theta}$ denote the stiffness and damping coefficients of the $i$th isolator in the $\theta$ direction, respectively. All of the isolators form the total uncoupled story pre-yielding stiffness coefficients, $k_{bex}(=\sum_i k_{iex})$, $k_{bey}(=\sum_i k_{iey})$, and $k_{b\theta}(=\sum_i k_{i\theta})$, and damping coefficients, $c_{bx}(=\sum_i c_{ix})$, $c_{by}(=\sum_i c_{iy})$, and $c_{b\theta}(=\sum_i c_{i\theta})$, in the $x$, $y$, and $\theta$ directions, respectively; the resilient force (base shear) of the isolation system is applied at center of rigidity (CR). The CR is eccentric from the center of mass (CM) at distances $e_x$ and $e_y$ in the $x$ and $y$ directions, respectively. Accordingly, the equations of motion of an asymmetric base-isolation building with LRBs can be expressed as

$$m_p\ddot{y}_p + c_{by}\dot{y}_p + c_{by}e_x\dot{\theta}_p + h_{by}(y_p) + k_{bey}e_x\theta_p = -m_p\ddot{y}_g \quad (1)$$

$$m_p\ddot{x}_p + c_{bx}\dot{x}_p - c_{bx}e_y\dot{\theta}_p + h_{bx}(x_p) - k_{bex}e_y\theta_p = -m_p\ddot{x}_g \quad (2)$$

$$\begin{aligned} &J_p\ddot{\theta}_p - c_{bx}e_y\dot{x}_p + c_{by}e_x\dot{y}_p + (c_{b\theta} + c_{bx}e_y^2 + c_{by}e_x^2)\dot{\theta}_p \\ &- h_{bx}(x_p)e_y + h_{by}(y_p)e_x + (k_{bex}e_y^2 + k_{bey}e_x^2 + k_{b\theta})\theta_p = 0 \end{aligned} \quad (3)$$

where $x_p$, $y_p$, and $\theta_p$ respectively represent the displacement in the $x$, $y$, and $\theta$ directions at the CM of the building relative to the ground; $h_{bx}(\bullet)$ and $h_{by}(\bullet)$ refer to the restoring forces of the LRBs in the corresponding direction; and $\ddot{x}_g$ and $\ddot{y}_g$ respectively are the horizontal ground accelerations in the $x$ and $y$ directions.

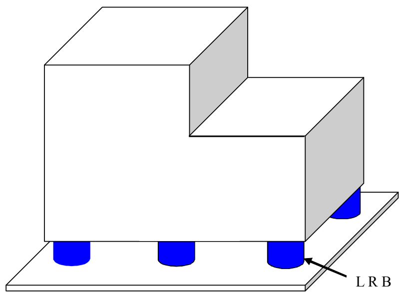


Fig 1: Rigid body superstructure base-isolation model

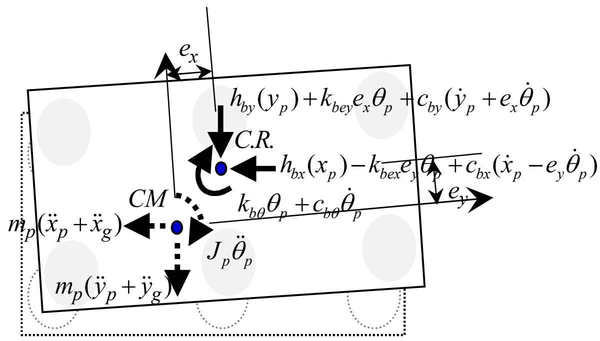


Fig 2: Free body diagram and applied forces of the base-isolated superstructure

## III. Bilinear Hysteretic Model

The restoring forces, $h_{bx}(\bullet)$ and $h_{by}(\bullet)$, are path-dependent for nonlinear isolation systems. In general, hysteresis loops are smooth except at the turning points. A hysteresis loop can be uniquely characterized by a backbone (skeleton) curve. Under steady-state cyclic loadings, the hysteretic behavior of nonlinear systems can be reconstructed using Masing's criterion [5, 9], whereby the unloading and reloading portion of a hysteresis loop is assumed to follow the same shape as the skeleton curve with the magnitude expanded by a factor of two and the origin translated to the projection of the point of force reversal onto the horizontal axis, as illustrated in Fig. 3. The restoring force in the $y$ direction is discretized and expressed after the first unloading as

$$h_{by}(y_p^i) = h_{by}(y_p^I) + 2f_{by}\left(\frac{y_p^i - y_p^I}{2}\right) \quad (4)$$

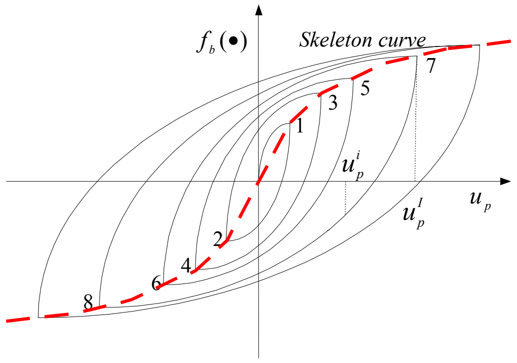


Fig 3: Hysteresis loops in relation to the skeleton curve

where $I$ is the instant of the most recent loading reversal; $y_p^i$ is the displacement in the $y$ direction at instant $i$ where $i = I, I+1, \ldots\ldots$; and $f_{by}(\bullet)$ is a single-valued function representing the skeleton curve, assumed to be bilinear, of three line segments with slopes of $k_{bey}$ or $k_{byy}$, expressed as

$$f_{by}(v) = \begin{cases} k_{bey}v & when\ -D \le v \le D \\ b_{by} + k_{byy}v & when\ v > D \\ -b_{by} + k_{byy}v & when\ v < -D \end{cases} \quad (5)$$

where $D$ denotes the yielding displacement and $b_{by}$ is the characteristic strength.

When Equation (4) is substituted into Equation (1), the governing equation of the $y$ direction at the CM of the building at instant $i$ becomes

$$\ddot{y}_p^i + \frac{c_{by}}{m_p}\dot{y}_p^i + \frac{c_{by}e_x}{m_p}\dot{\theta}_p^i + \frac{h_{by}(y_p^I) + 2f_{by}\left(\frac{y_p^i - y_p^I}{2}\right)}{m_p} + \frac{k_{bey}e_x}{m_p}\theta_p^i = -\ddot{y}_g^i \quad (6)$$

At instant $i = I$, Equation (6) is reduced to

$$\ddot{y}_p^I + \frac{c_{by}}{m_p}\dot{y}_p^I + \frac{c_{by}e_x}{m_p}\dot{\theta}_p^I + \frac{h_{by}(y_p^I)}{m_p} + \frac{k_{bey}e_x}{m_p}\theta_p^I = -\ddot{y}_g^I \quad (7)$$

Substituting Equation (7) for $h_{by}(y_p^I)/m_p$ into Eq. (6) yields

$$(\ddot{y}_p^i - \ddot{y}_p^I) + \frac{c_{by}}{m_p}(\dot{y}_p^i - \dot{y}_p^I) + \frac{c_{by}e_x}{m_p}(\dot{\theta}_p^i - \dot{\theta}_p^I) + \frac{2f_{by}\left(\frac{y_p^i - y_p^I}{2}\right)}{m_p} + \frac{k_{bey}}{m_p}(\theta_p^i - \theta_p^I) = -(\ddot{y}_g^i - \ddot{y}_g^I) \quad (8)$$

After defining

$$\ddot{u}_p^i = \ddot{y}_p^i - \ddot{y}_p^I,\ u_\theta^i = \theta_p^i - \theta_p^I,\ \ddot{u}_g^i = \ddot{y}_g^i - \ddot{y}_g^I \quad (9)$$

in Equation (9) and substituting it into Equation (8), the governing equation can be rewritten as

$$\ddot{u}_p^i + \frac{c_{by}}{m_p}\dot{u}_p^i + \frac{2f_{by}(u_p^i/2)}{m_p} = -\ddot{u}_g^i - \frac{c_{by}e_x}{m_p}\dot{u}_\theta^i - \frac{k_{bey}e_x}{m_p}u_\theta^i \quad (10)$$

Substituting Equation (5) into Equation (10), and denoting the right-hand side of Equation (10) as $\ddot{u}_{g\theta}^i$, the governing equation can be rewritten as

$$\ddot{u}_p^i + \frac{c_{by}}{m_p}\dot{u}_p^i + \frac{k_{bey}}{m_p}u_p^i = \ddot{u}_{g\theta}^i \qquad -D \le u_p^i/2 \le D \quad (11)$$

$$\ddot{u}_p^i + \frac{c_{by}}{m_p}\dot{u}_p^i + \frac{2b_{by}}{m_p} + \frac{k_{byy}}{m_p}u_p^i = \ddot{u}_{g\theta}^i \qquad u_p^i/2 > D \quad (12)$$

$$\ddot{u}_p^i + \frac{c_{by}}{m_p}\dot{u}_p^i - \frac{2b_{by}}{m_p} + \frac{k_{byy}}{m_p}u_p^i = \ddot{u}_{g\theta}^i \qquad u_p^i/2 < -D \quad (13)$$

Eqs. (11)–(13) are employed to identify the parameters in the $y$ direction of the isolation system of the asymmetric base-isolation building.

## IV. Physical Identification

Identification of the system parameters can be conducted as long as the dynamic responses of the structure subjected to the input excitation are available [10]. According to an output error concept [11], the system parameters are obtained by minimizing the discrepancies between the recorded and predicted responses of the system. The system parameters so evaluated are considered optimal. Using the first set of data and Equation (11), the partial measure of fit is defined as

$$e_1 = \sum_{i=1}\left[\ddot{u}_p^i + \frac{c_{by}}{m_p}\dot{u}_p^i + \frac{k_{bey}}{m_p}u_p^i - \ddot{u}_{g\theta}^i\right]^2 \quad (14)$$

The values of $c_{by}$ and $k_{bey}$ can be obtained by solving the simultaneous equations

$$\frac{\partial e_1}{\partial(c_{by}/m_p)} = 0 \quad , \quad \frac{\partial e_1}{\partial(k_{bey}/m_p)} = 0 \quad (15)$$

 

Similarly, applying the second data set and Equation (12) produces another partial measure of fit:

$$e_2 = \sum_{i=1} \left[ \ddot{u}_p^i + \frac{c_{by}}{m_p}\dot{u}_p^i + \frac{2b_{by}}{m_p} + \frac{k_{byy}}{m_p}u_p^i - \ddot{u}_{g\theta}^i \right]^2 \tag{16}$$

The minimization of $e_2$ by solving the simultaneous equations

$$\frac{\partial e_2}{\partial (c_{by}/m_p)} = 0, \frac{\partial e_2}{\partial (2b_{by}/m_p)} = 0, \frac{\partial e_2}{\partial (k_{byy}/m_p)} = 0 \tag{17}$$

yields the values of $c_{by}$, $b_{by}$, and $k_{byy}$. Finally, the minimization of $e_3$, which is related with the third data set, and Equation (13) results in another set of values of $c_{by}$, $b_{by}$ and $k_{byy}$. Parameter values from various databases differ; thus, an average value is adopted. The global measure of fit is defined as the sum of all partial ones:

$$e = e_1 + e_2 + e_3 \tag{18}$$

Therefore, among the sets of $c_{by}$, $b_{by}$, $k_{bey}$, and $k_{byy}$, the set that yields a minimum global measure of fit is regarded as the solution. Similarly, *x* directional physical parameters of the isolation story could be obtained using Equation (2) and the aforementioned procedures. Finally, by substituting the bidirectional physical parameters derived in the previous step into Equation (3), $\theta$ directional parameters of the isolation story could be obtained using the aforementioned procedures. To compare the convergence and accuracy of the identification process, the error index is defined as

$$EI = \left\{ \frac{\int_0^t \left[ (\ddot{y}_p)_r - (\ddot{y}_p)_t \right]^2 dt}{\int_0^t \left[ (\ddot{y}_p)_r \right]^2 dt} \right\}^{1/2} \tag{19}$$

where $(\ddot{y}_p)_r$ is the recorded or measured *y* directional acceleration response at the CM of the building floor and $(\ddot{y}_p)_t$ is the corresponding theoretical or predicted response. $(\ddot{y}_p)_t$ is calculated from the identified system parameters with the recorded input excitation. When $y$ is replaced by $x$ or $\theta$, Equation (19) represents the error index for the $x$ or $\theta$ direction. In general, the measured responses $(\ddot{x}_p)_r$, $(\ddot{y}_p)_r$, and $(\ddot{\theta}_p)_r$ at the CM are indirectly obtained using measurements from three uniaxial sensors horizontally placed at three different locations on a floor, with two sensors along the same direction and the third along a different direction.

## V. NUMERICAL EXAMPLE

To verify the proposed methodology for system identification of asymmetric buildings, a numerical example is considered using a base-isolated model of a rigid superstructure with LRBs as the isolators. The system parameters considered are as follows: $m_p = 250.0 \times 10^3$ kg, $J_p = 7400.0$ t-m$^2$; $c_{bx} = c_{by} = 146.0$ kN.s/m, $c_{b\theta} = 642.0$ kN.m.s; $b_{bx} = b_{by} = 245.25$ kN, $k_{bex} = k_{bey} = 44.145$ MN/m, $k_{byx} = k_{byy} = 6.867$ MN/m, $k_{b\theta} = 4974.00$ MN.m; $e_x = 1.0$ m, $e_y = 1.0$ m.

The dynamic responses of the asymmetric base-isolated building under the E–W and N–S components of the 1940 El Centro earthquake are calculated using Newmark's linear acceleration method with a time step of 0.02 sec. The acceleration responses contaminated with an artificial white noise of 5% noise-to-signal ratio are considered in the system identification analysis to simulate the measured data in a more realistic manner.

Figs. 4 and 5 present the nonlinear restoring forces of the isolators in the *y* and *x* directions, respectively. The force–displacement relationship in torsion ($\theta$ direction) is illustrated in Fig. 6.

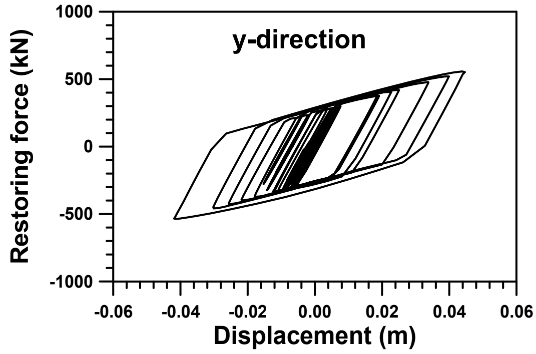


Fig. 4: Nonlinear restoring force of LRBs in the *y* direction.

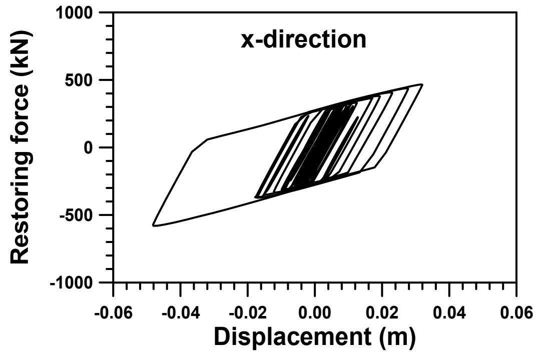


Fig 5: Nonlinear restoring force of the LRBs in the *x* direction

 

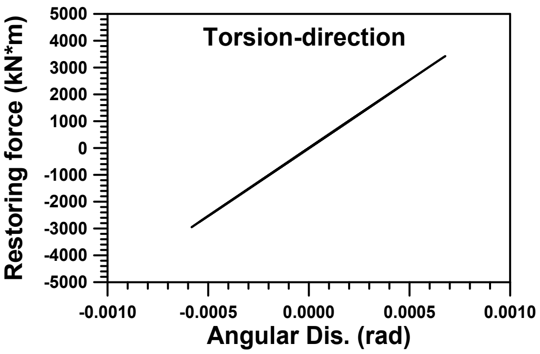


Fig 6: Restoring force in relation to the rotational displacement of the LRBs.

In the first cycle of identification, the initial value of $c_{by}e_x$ is arbitrarily set as 0. The global measure of fit as a function of $k_{by}e_x$ is presented in Fig. 7, from which the least-squares estimate of $k_{bey}e_x$ is determined to be 45.0 MN. Subsequently, $k_{bey}e_x$ is fixed at this value (45.0 MN), under which the minimization process is further performed. As illustrated in Fig. 8, the optimal estimate of $c_{by}e_x$ is now determined to be 150.0 kN.s. Meanwhile, the physical parameters of the LRBs in the $y$ direction are identified as $c_{by} = 152.0$ kN.s/m, $b_{by} = 244.00$ kN, $k_{bey} = 44.088$ MN/m, and $k_{byy} = 6.909$ MN/m.

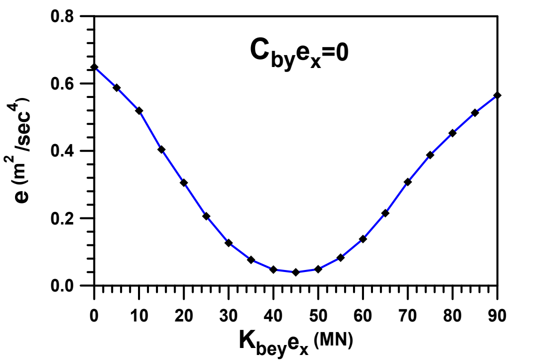


Fig 7: Global measure of fit in the first cycle with $c_{by}e_x = 0$ kN.s

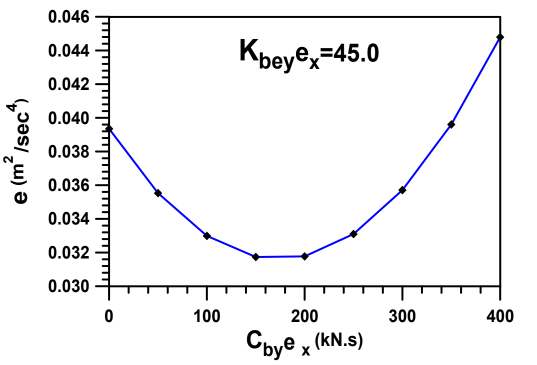


Fig 8: Global measure of fit in the first cycle with $k_{bey}e_x = 45$ MN.

The second identification cycle is then implemented with the initial value of $c_{by}e_x$ at 150.0 kN.s. Minimization of the global measure of fit leads to $k_{bey}e_x = 44.0$ MN, as illustrated in Fig. 9. The numerical results suggest that three cycles of identification are sufficient in this example. Table 1 summarizes the system parameters of the LRBs in the $y$ direction identified after three iterations. All other parameters for the $x$ and $\theta$ directions of the isolation system are further determined using similar procedures and the results are listed in Tables 2 and 3, respectively.

Table 1: Identified structural parameters of the LRBs in the $y$ direction

| Number of cycle | $y$-direction | | | | $\theta$-direction | |
|---|---|---|---|---|---|---|
| | $c_{by}$ kN.s/m | $b_{by}$ kN | $k_{byy}$ MN/m | $k_{bey}$ MN/m | $c_{by}e_x$ kN.s | $k_{bey}e_x$ MN |
| 1 | 152.0 | 244.00 | 6.909 | 44.088 | 150.0 | 45.0 |
| 2 | 152.0 | 244.00 | 6.898 | 44.085 | 175.0 | 44.0 |
| 3 | 152.0 | 244.00 | 6.902 | 44.088 | 174.0 | 44.4 |
| True Value | 146.0 | 245.25 | 6.867 | 44.145 | 146.0 | 44.145 |
| E.I. | 0.1272 | | | | | |

Table 2: Identified structural parameters of the LRBs in the $x$ direction

| Number of cycle | $x$-direction | | | | $\theta$-direction | |
|---|---|---|---|---|---|---|
| | $c_{bx}$ kN. s/m | $b_{bx}$ kN | $k_{byx}$ MN/m | $k_{bex}$ MN/m | $c_{bx}e_y$ kN.s | $k_{bex}e_y$ MN |
| 1 | 157.0 | 241.05 | 7.021 | 43.917 | 150.0 | 45.0 |
| 2 | 157.0 | 241.05 | 7.009 | 43.918 | 135.0 | 44.0 |
| 3 | 157.0 | 241.06 | 7.011 | 43.911 | 133.0 | 44.2 |
| True Value | 146.0 | 245.25 | 6.867 | 44.145 | 146.0 | 44.145 |
| E.I. | 0.1257 | | | | | |

Table 3: Identified structural parameters of the LRBs in the $\theta$ direction

| Number of cycle | $c_{b\theta}$ (kN · m · s) | $k_{b\theta}$ (MN · m) |
|---|---|---|
| 1 | 665.4 | 4965.58 |
| 2 | 665.3 | 4966.24 |
| 3 | 664.8 | 4967.55 |
| True Value | 642.0 | 4974.00 |
| E.I. | 0.3855 | |

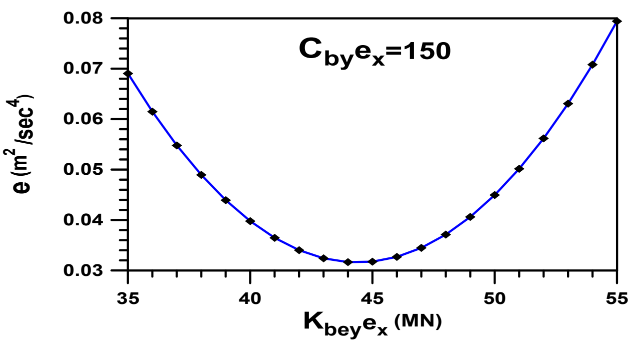


Fig: 9: Global measure of fit in the second cycle with $c_{by}e_x = 150$ kN.s.

 

The numerical results in this example suggest that three iterative cycles of identification are sufficient and yield acceptable accuracy. The skeleton curve estimated from the identified parameters of the LRBs in the *y* direction is illustrated in Fig. 10. Comparisons of the acceleration and displacement responses of the structure in the *x* direction are shown in Figs. 11 and 12, respectively; the corresponding comparisons for the *y* direction are shown in Figs. 13 and 14, respectively; and those for the $\theta$ direction are shown in Figs. 15 and 16, respectively. The time histories predicted using the identified parameters are highly similar to those of the analytical model.

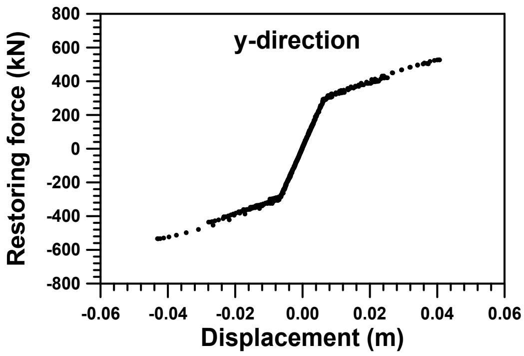


Fig 10: Identified skeleton curve of the LRBs in the *y* direction.

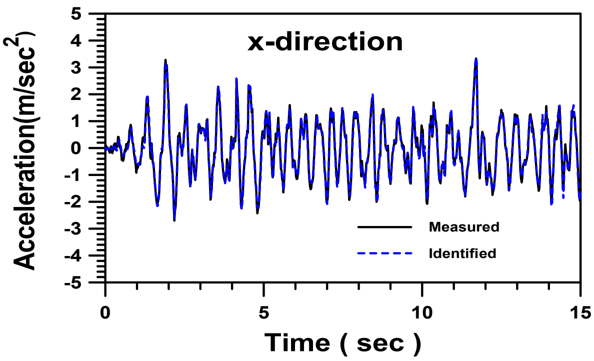


Fig 11: Comparison between identified and measured accelerations of the building in the *x* direction

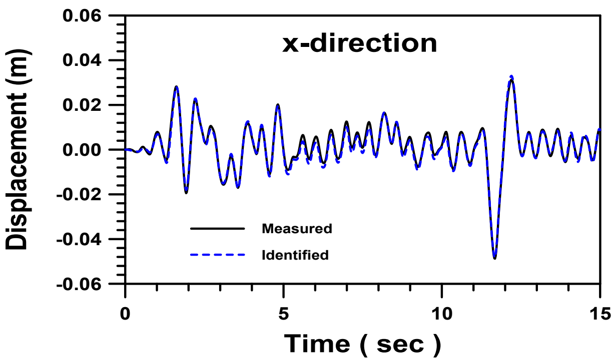


Fig 12: Comparison between identified and measured displacements of the building in the *x* direction

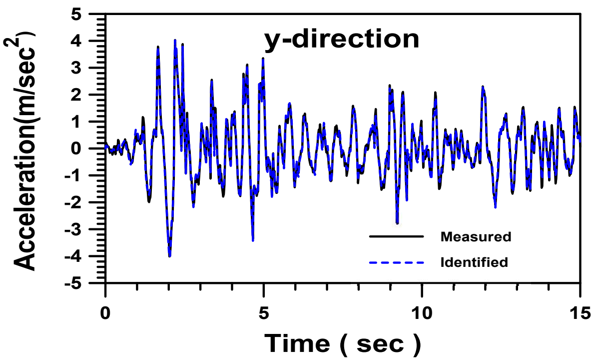


Fig 13: Comparison between identified and measured accelerations of the building in the *y* direction

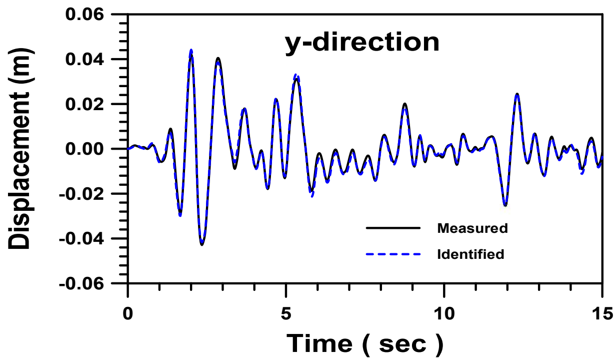


Fig 14: Comparison between identified and measured displacements of the building in the *y* direction

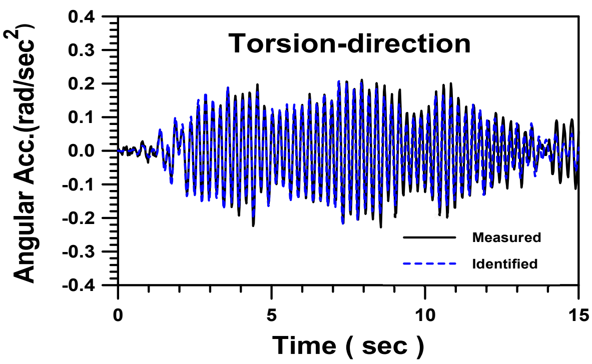


Fig 15: Comparison between identified and measured torsional accelerations of the building

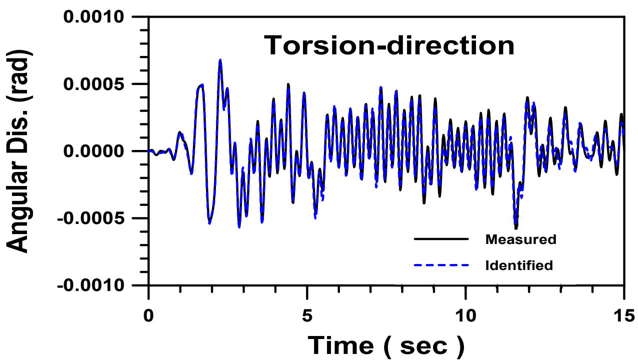


Fig 16: Comparison between identified and measured torsional displacements of the building

## VI. Conclusion

In this paper, a physical identification procedure of asymmetric base-isolation buildings equipped with LRBs is developed. The hysteretic behavior of the nonlinear system is characterized by a backbone curve, by which the multivalued restoring force is transformed into a single-valued function; consequently, the system identification analysis of inelastic structures is greatly simplified. The feasibility of the proposed scheme is demonstrated using the numerical example of an asymmetric base-isolation system supporting a rigid superstructure subjected to bidirectional earthquake ground excitations. Features of the proposed procedure include:

(a) All physical parameters of the isolated system in terms of the bilinear translational stiffness in both the $x$ and $y$ directions, torsional stiffness, and damping coefficients can be identified.

(b) The system parameters are identified with reasonable accuracy in three iterations, even in the presence of noise contamination. The robustness of the algorithm makes it a favorable alternative for practical applications.

(c)The proposed algorithm extracts the physical parameters of the system, which reveals the actual behavior of nonlinear systems more than does using modal parameters representing only equivalent linear systems.

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